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Simulation and experimental study on thermal optimization of the heat exchanger for automotive exhaust-based thermoelectric generators

C.Q. Su*, W.S. Wang, X. Liu, Y.D. Deng

Hubei Key Laboratory of Advanced Technology for Automotive Components, Automobile Engineering Institute, Wuhan University of Technology, 205 Luoshi Road, Hongshan District, Wuhan 430070, China

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ABSTRACT

Thermoelectric technology has revealed the potential for automotive exhaust-based thermoelectric generator (TEG), which contributes to the improvement of the fuel economy of the engine-powered vehicle. As a major factor, thermal capacity and heat transfer of the heat exchanger affect the performance of TEG effectively. With the thermal energy of exhaust gas harvested by thermoelectric modules, a temperature gradient appears on the heat exchanger surface, so as the interior flow distribution of the heat exchanger. In order to achieve uniform temperature distribution and higher interface temperature, the thermal characteristics of heat exchangers with various heat transfer enhancement features are studied, such as internal structure, material and surface area. Combining the computational fluid dynamics simulations and infrared test on a high-performance engine with a dynamometer, the thermal performance of the heat exchanger is evaluated. Simulation and experiment results show that a plate-shaped heat exchanger made of brass with accordion-shaped internal structure achieves a relatively ideal performance, which can practically improve overall thermal performance of the TEG.

1. Introduction

Approximately 40% of the fuel energy is lost in exhaust gas according to energy balance of a combustion engine, which intense the energy crisis and environment pollution [1]. As one way to recover waste heat,Thermoelectric generation (TEG) technology can recover waste heat from the exhaust and convert thermal energy into electrical energy with the advantages of being highly reliable, zero emission,low noise and involving no moving parts. Thermoelectric modules (TEMs) made of semiconductor materials are sandwiched between the heat exchanger and the cooling unit in an exhaust-based thermoelectric generation. This sandwich structure is kept by the clamping devices. Exhaust gas flows into the hot-side heat exchanger through a bypass to form the hot source. Cooling water pumps into the cooling water tanks to form the cooler. The electric power is generated as a result of the temperature difference based on the Seebeck effect [2]. The schematic diagram of TEGs system is shown in Fig. 1.

In order to get higher thermoelectric efficiency and generation capacity, the heat exchanger's geometry, mounted location, contact area with thermoelectric modules, operating conditions and so on were optimized by numerical analyses and experiments. Astrain et al. [3] optimized the influence of heat exchangers' thermal resistances (in both the hot and cold

* Corresponding author. Tel.: +86 18971577512; fax: +86 2787859667
E-mail addresses: 455060965@qq.com, suchuqi@whut.edu.cn (C.Q. Su).

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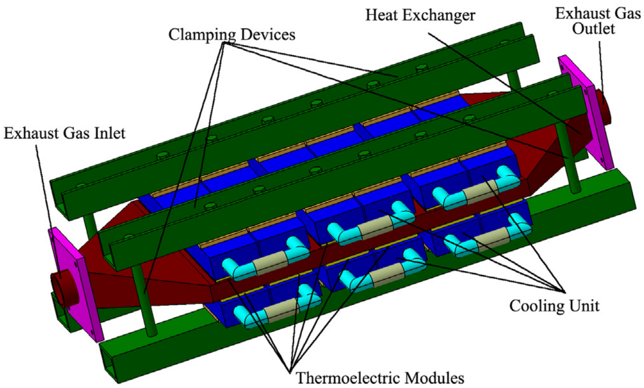

Fig. 1. Schematic diagram of TEGs system.

side) and pressure drops by CFD [4] to maximize the electric power generated. The geometrical effect of TEG on heat transfer characteristics was investigated in a parallel micro channel heat sink [5].Optimization of the heat exchanger aims to increase the overall efficiency of TEG, which involves two major tasks: maintaining a sufficient temperature difference across the thermoelectric models (TEMs) and reducing thermal losses of the system. In the same irrelevant conditions, such as exhaust condition, cooling condition, raising the interface temperature by improving the thermal performance of the heat exchanger can obviously increase the overall efficiency of the TEG. Due to the constraints of a single module's size and performance, a certain number of TEMs are usually tiled between the heat exchanger and the cooler with a series–parallel connection [6]. As the thermal energy of exhaust gas harvested, the temperature gradient will appear on the heat exchanger surface, which reduces the electricity generation of TEMs in return. In order to utilize the performance of each TEM, it is essential to optimize the heat exchanger to get uniform temperature distribution.

2. Thermal simulation of the heat exchanger

Computational fluid dynamics (CFD) software is used to simulate the exhaust gas flow within the heat exchanger, presenting the temperature distribution [7]. Internal structure, material and thickness of the heat exchanger are changed to obtain the ideal thermal field simulation results.

2.1. Boundary condition of simulation model

Simulation model is assured that the exhaust flow in the heat exchanger is fully turbulent and molecular viscosity can be neglected, so the standard κ–ε model is adopted in the CFD simulation. As Near wall area processing with standard wall function, the natural convection heat transfer coefficient and the environment temperature are set.

The automobile exhaust was approximately 300–500 kPa in pressure and 500–700 °C in temperature when just discharged from the engine cylinder [8], the gas inlet temperature is set to 400 °C, which can take advantage of the performance of TEMs applied in the TEG. Base on the working operating characteristics of the engine, the inlet flow velocity can reach 20 m/s. Considering the acoustic attenuation performance of the TEG, the traditional muffler is replaced on the test bench [9]. The outlet of the mixing flow use the pressure boundary condition, the gauge pressure at the outlet is set to 0 Pa. In addition, the heat transfer coefficient between the external surface of the heat exchanger and the air is set to 20 W/(m^2 K) with the environmental temperature is set to 25 °C.

As for the heat exchanger presenting an approximately axial symmetry in geometry, so the flow, pressure and temperature fields also show axisymmetric characteristics in the absence of ambient winds.

3. Simulation results and analysis

By applying fundamental formula of heat transfer $\Phi = hA\triangle T$, heat convection can be greatly strengthened by the increase of the heat transfer area *A*. This target can be approached by changing the structure of the conduction surface by fitting baffles. Another approach is to increase the heat transfer coefficient h.

According to the fluid dynamics theories, under the condition of Reynolds number Re > 104, macro turbulent fluid flow is a significant impact factor on improving the heat transfer. Moreover, the greater the heat transfer coefficient *h*, the better the heat transfer quantity. The thermal resistance of turbulent flow convection mostly exist in the boundary layer.

The field synergy principle was proposed as another indication of the synergy degree between velocity and temperature field for the entire flow and heat transfer domain, the better the synergy was between the temperature field and velocity field, the better the heat transfer [10]. According to both theories above, the strengthening of the heat transfer can be approached by adding turbulence devices to enhance the fluid disturbance and damage the boundary layer [11].

3.1. Temperature field on the heat exchanger surface with different inter structures

On the basic of the theories of thermal convection and turbulent flow as mentioned above, the three-dimensional models of heat exchangers with different internal structures are put forward by fitting baffles. Among these internal structure, the geometrical model of the heat exchanger including fishbone-shaped internal structure, accordion-shaped internal structure, scatter-shaped internal structure are showed in Fig. 2a,b,c. The CFD simulation results including the temperature contour are showed in Fig. 3a–c.

As the simulation indicates, the accordion-shape and the fishbone-shape have a slightly higher interface temperature than the scatter-shape on the whole in the direction of *Z*-axis, especially the temperature at the outlet. However, the accordion-shape design presents a better uniform temperature distribution than of the fishbone-shape. Considering the temperature distribution, the heat exchanger with accordion-shape internal structure is more ideal for TEG.

3.2. Temperature field on the exhaust Gas Tanks with different surface area

In order to increase the electricity generation of the TEG application, TEMs are desirable to be arranged as much as possible, which needs the greater surface area. As a result, the heat exchanger will become much bigger and heavier, which is not beneficial for waste gas spreading to improve the surface temperature. The surface area is another issue to thermal optimization of the heat exchanger besides the internal structure.

According to the demand of TEMs arrangement, the heat exchangers with different surface areas are designed, which are 598 mm × 250 mm, 660 mm × 305 mm and 775 mm × 365 mm. For simulation comparison, the internal structures of these three heat exchangers are the accordion-shape and the other boundary conditions are kept the same. The simulation results are shown in Fig. 4a–c.

From the simulation result, the temperature distributions of the three heat exchangers are roughly same: higher uniform temperature distribution. In order to increase the overall output power of the TEG application, the electricity generation of a

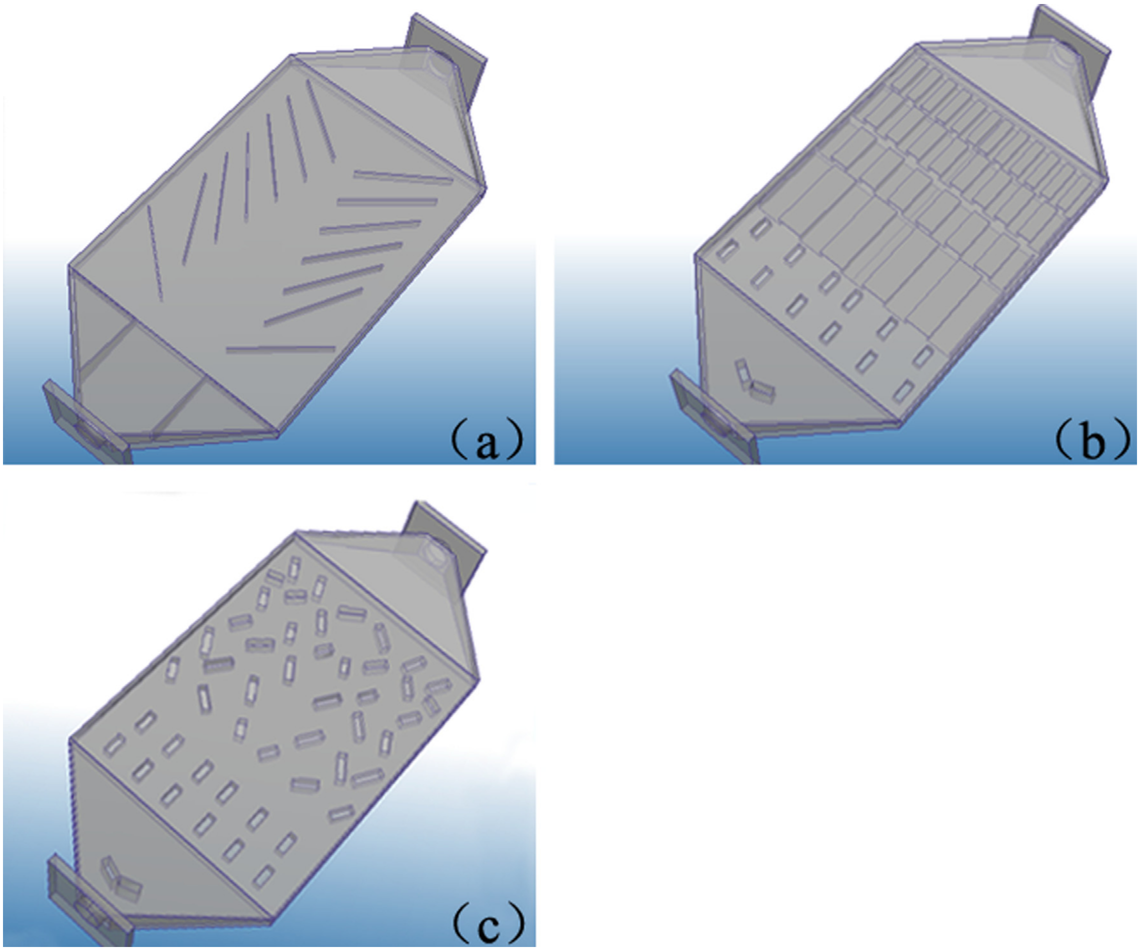

Fig. 2. Three-dimensional model of the (a) fishbone-shaped, (b) accordion-shaped and (c) scatter-shaped heat exchanger.

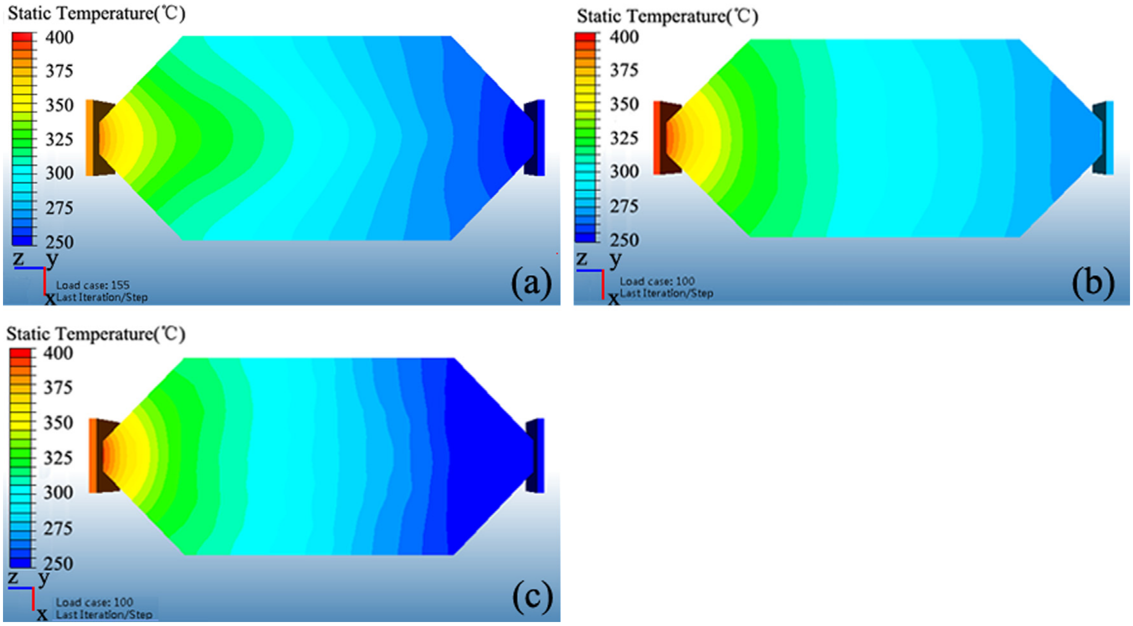

Fig. 3. Simulation results of the (a) fishbone-shaped, (b) accordion-shaped and (c) scatter-shaped heat exchanger.

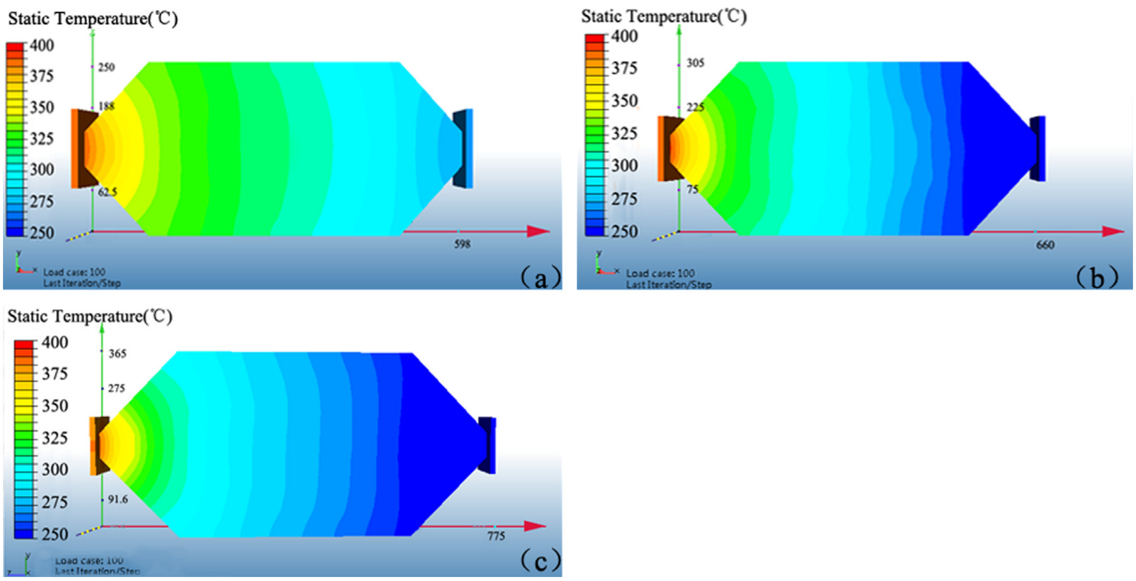

Fig. 4. Simulation results of the exchanger with (a) 598 mm × 250 mm, (b) 660 mm × 305 mm and (c) 775 mm × 365 mm surface area.

signal TEM should not be too low. With the terminal temperature showing a decreasing trend as the surface area increases, the quantity of TEMs and surface area of the exchanger should be balanced together based on actual conditions.

3.3. *Temperature field on the exhaust gas tanks with different materials*

In addition, material is a significant factor for the thermal performance of the heat exchanger which not only impacts the thermal conductivity directly but also dominates the uniformity of thermal stress in device level and module level. A non-uniform thermal stress could make the contact of the TEMs and heat exchanger rough [12]. Based on the reason above, iron and brass are selected for the heat exchanger material and CFD simulation results are showed in Fig. 5a,b.

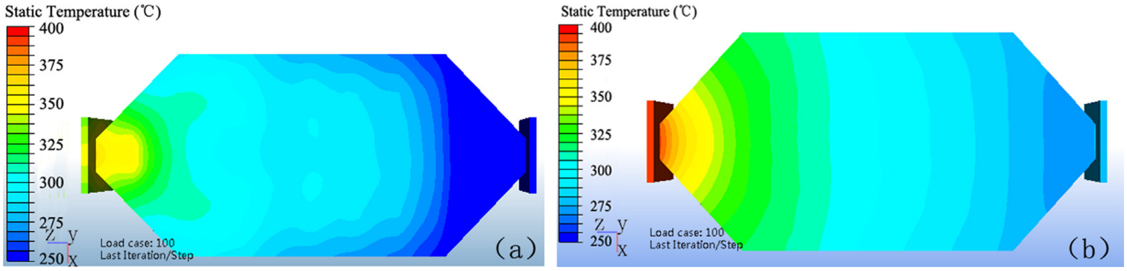

Fig. 5. Simulation results of the exchanger made of (a) iron and (b) brass.

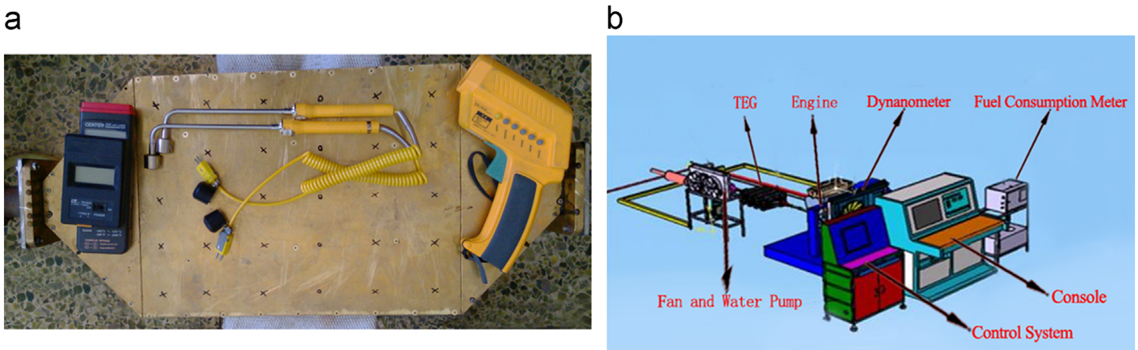

Fig. 6. Automotive exhaust TEG experimental system.

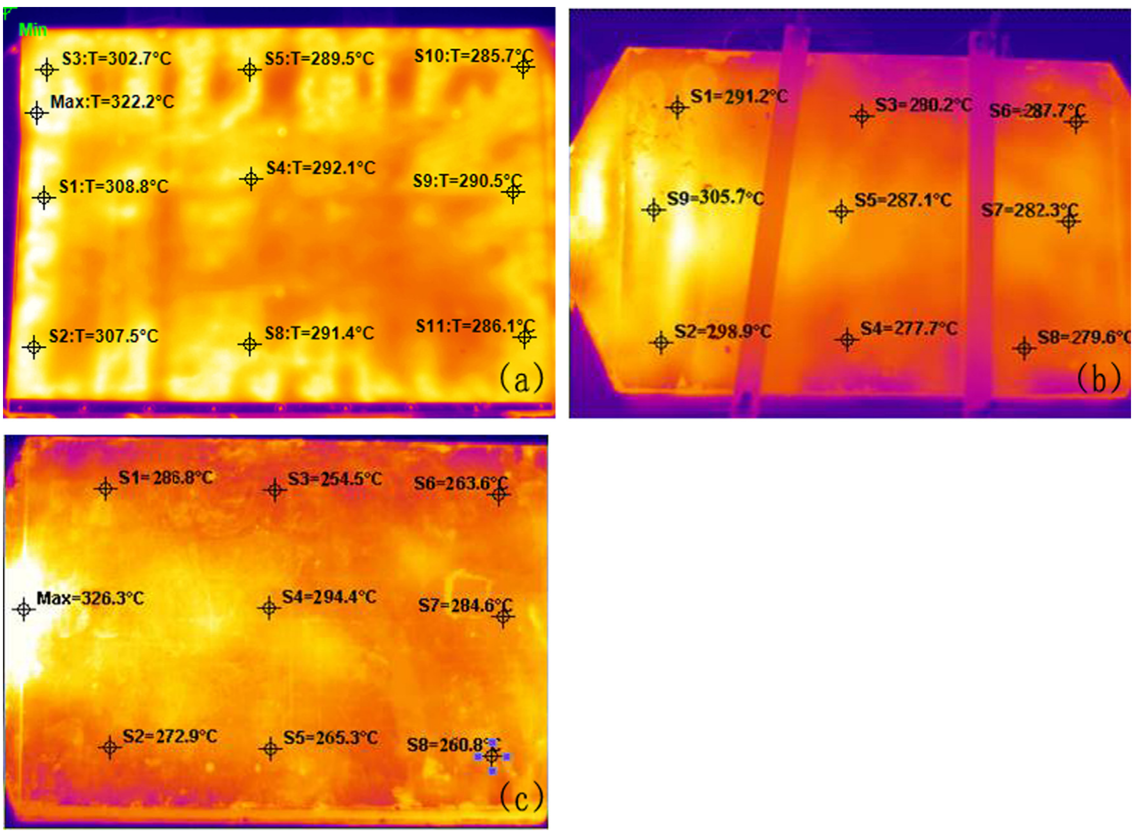

Fig. 7. Infrared experiment results of the (a) accordion-shaped, (b) scatter-shaped and (c) fishbone-shaped internal structure.

4. Analysis on the experimental results

4.1. Experimental system and bench test

The CFD simulation results above should be verified by experiment. Automotive exhaust TEG experimental system (Fig. 6) consists of a four-cylinder engine, a dynamometer and a whole exhaust system. Taking the working performance of the TEG into consideration, it is reasonable to install the heat exchanger after the catalytic converter. The exhaust heat is used as the hot source and an independent circulating coolant system as the cold source. Apart from the k-type thermocouples, infrared thermal imaging system is used to image the surface temperature distribution on the heat exchangers with different internal structures and varied surface areas. During the bench test, the external surface of the heat exchanger is clean, smooth and exposed to the ambient. The experiment conditions including the ambient temperature, atmospheric humidity, etc. are kept the same. The engine's speed is maintained at around 3350 rpm and the output power is remained unchanged.

4.2. Temperature field on the heat exchanger surface with different inter structures

Pictures of the surface temperature field on the different heat exchangers with three kinds of internal structures including fishbone shape, accordion shape and scatter shape, are taken by the infrared thermal imaging system, and compared in Fig. 7a–c. All of the heat exchangers are made of iron of 5 mm thickness with the same surface area (660 mm × 305 mm).

In terms of surface temperature and uniformity of the whole temperature distribution, the experiment results for these kinds of internal structures are similar to the simulation results. The heat exchanger with the fish-bone shaped structure

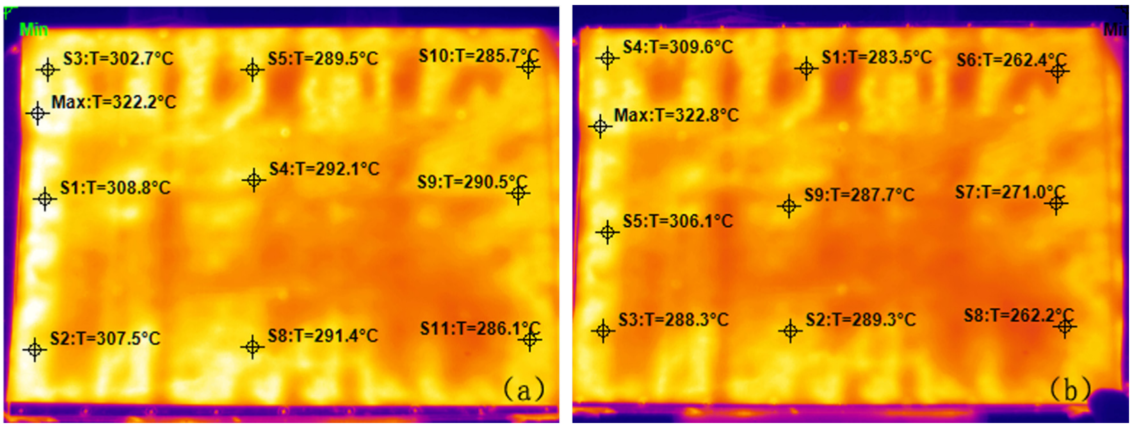

Fig. 8. Infrared experiment results of the (a) brass and (b) iron heat exchanger.

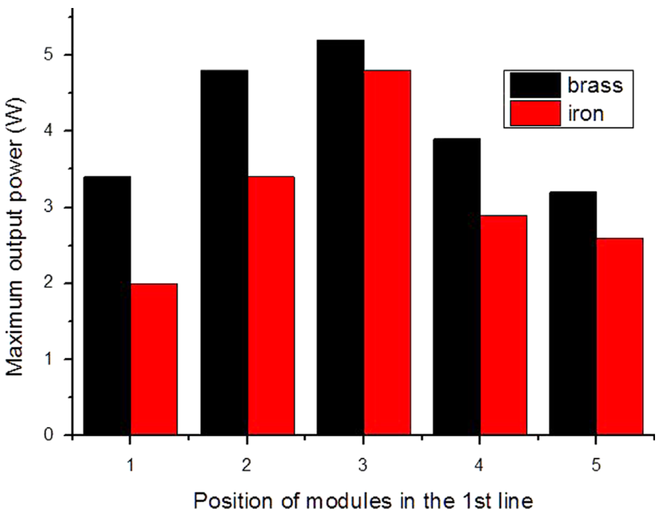

Fig. 9. The power output of each piece of thermoelectric modules placed on the front end of the brass or iron heat exchanger.

presents the worse uniform temperature distribution. Besides, the heat exchanger with the accordion-shaped structure has a slightly higher temperature than that of the scatter-shaped structure, so is the maximum temperature. Overall, the accordion-shaped structure tends to be adopted in the subsequent application.

4.3. *Temperature field on the heat exchanger surface with different materials*

Pictures of the surface temperature field on the heat exchanger made of iron and brass are taken by the infrared thermal imaging system. Both heat exchangers are with the internal structure of the accordion shape and 5 mm thickness. The experimental results are shown in Fig. 8a,b.

Based on the experiment results, the temperature and the whole temperature distribution coincide with those of the simulation results. It is obvious that the thermal performance of the brass is much better than that of the iron one.

To further verify this conclusion, two sets of eight pieces of TEMs are placed on the front end of the heat exchanger, aiming at testing the power output of the modules by an electronic load.

Both experiments were carried out under the same experiment conditions. The results are shown in Fig. 9. In conclusion, modules on the brass exchanger have higher output power than those on the iron heat exchanger.

5. Conclusion

In this work, the heat exchanger attached with TEGs for recovering waste heat from an automotive exhaust pipe is analyzed. According to the agreement between the infrared experimental results and the CFD simulation results, a brass heat exchanger with accordion shape and surface area (660 mm $\times$ 305 mm) is selected to form the hot side. It can reduce the thermal resistance (between the exchanger and the TEMs), and obtain a relatively high surface temperature and uniform temperature distribution to improve the efficiency of the TEG.

The current study focuses on the structural optimization of the heat exchanger and the coolant system to improve the efficiency of the vehicular exhaust gas heat. In the later study, the way of the simulation modeling and the infrared experimental verification that has been introduced in this article needs to be combined with the heat transfer theory, to make further structural design and optimization to improve the overall exhaust heat utilization.

Acknowledgments

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